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Less Minimal Supersymmetric Standard Model*

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Abstract

Most of the phenomenological studies of supersymmetry have been carried out using the so-called minimal supergravity scenario, where one assumes a universal scalar mass, gaugino mass, and trilinear coupling at M_{GUT} . Even though this is a useful simplifying assumption for phenomenological analyses, it is rather too restrictive to accommodate a large variety of phenomenological possibilities. It predicts, among other things, that the lightest supersymmetric particle (LSP) is an almost pure B-ino, and that the μ -parameter is larger than the masses of the $SU(2)_L$ and $U(1)_Y$ gauginos. We extend the minimal supergravity framework by introducing one extra parameter: the Fayet-Iliopoulos D -term for the hypercharge $U(1)$, D_Y . Allowing for this extra parameter, we find a much more diverse phenomenology, where the LSP is $\tilde{\nu}_\tau$, $\tilde{\tau}$ or a neutralino with a large higgsino content. We discuss the relevance of the different possibilities to collider signatures. The same type of extension can be done to models with the gauge mediation of supersymmetry breaking. We argue that it is not wise to impose cosmological constraints on the parameter space.

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Supersymmetry (SUSY) is regarded as one of the most promising extensions of the Standard Model. A supersymmetric version of the Standard Model will be the subject of exhaustive searches in this and the next generation of collider experiments.

The Lagrangian of the minimal supersymmetric extension of the Standard Model, the so-called “Minimal Supersymmetric Standard Model” (MSSM), consists of a SUSY-preserving piece and a SUSY-breaking piece[1]. The SUSY-preserving piece contains all of the Standard Model parameters plus the so-called μ -term, once R -parity is imposed to prevent baryon/lepton number violation. In this letter, we assume an exact or approximate R -parity, which implies that the lightest supersymmetric particle (LSP) does not decay inside detectors.

The SUSY-breaking Lagrangian will, ultimately, be determined by the physics of supersymmetry breaking and flavor but at the moment the best approach is to simply parameterize it with a general set of explicitly SUSY-breaking parameters. A general explicit soft SUSY-breaking Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{SUSY}} = & -m_{H_d}^2 |H_d|^2 - m_{H_u}^2 |H_u|^2 + (B\mu H_u H_d + \text{H.c.}) \\ & - \left(\mathcal{A}_d^{ij} \tilde{Q}_i \tilde{d}_j H_d + \mathcal{A}_u^{ij} \tilde{Q}_i \tilde{u}_j H_u + \mathcal{A}_l^{ij} \tilde{L}_i \tilde{e}_j H_d + \text{H.c.} \right) \\ & - \sum_F m_{\tilde{F}}^{2ij} \tilde{F}_i^\dagger \tilde{F}_j - \sum_{a=1,2,3} (M_a \lambda_a \lambda_a + \text{H.c.}),\end{aligned}\tag{1}$$

where $F = Q, L, U, D, E$ and $i, j = 1, 2, 3$ for each generation, contains more than 100 new parameters and makes the study of the MSSM parameter space completely inviable. Furthermore, a random choice of SUSY-breaking parameters is most likely ruled out, because of flavor changing effects and CP-violation. In light of this situation, simplifying assumptions are not only welcome but necessary.

The “minimal supergravity” framework is the most commonly used set of assumptions imposed on the MSSM. Because it has nothing to do with supergravity itself, we will refer to this framework as the “Very Minimal Supersymmetric Standard Model” (VMSSM), to avoid confusion. It assumes a universal scalar mass-squared, gaugino mass, and trilinear coupling ($m_{\tilde{F}}^{2ij} = m_0^2 \delta^{ij}$ for all $\tilde{F}$, $M_a = M_{1/2}$ for all a , and $\mathcal{A}_f^{ij} = A_0 \lambda_f^{ij}$ for all f , where λ_f^{ij} are the ordinary Yukawa couplings) at the grand unified (GUT) scale. The VMSSM is, therefore, parameterized by five real parameters: m_0^2 , $M_{1/2}$, A_0 , μ , and B [2].

More recently a lot of work has been done on models with the gauge mediation of SUSY breaking (GMSB)[3]. In models of this type again just five real parameters are introduced: F/M , M , N , μ , and B . It is important to note that the particle spectra of models with the GMSB are similar to those of the VMSSM [4] and we will, therefore, concentrate our discussion on the VMSSM and possible modifications to it.

The issue we would like to address is how restrictive the VMSSM is to collider phenomenology. It is important to be able to explore more diverse particle spectra while still satisfying all experimental bounds and keeping the number of parameters small. In this letter we propose a “Less Minimal Supersymmetric Standard Model” (LMSSM), which adds only one extra parameter to the VMSSM: the Fayet–Iliopoulos D -term for the $U(1)_Y$ gauge group, D_Y . Unlike the VMSSM, this framework will prove to be general enough to allow the following additional phenomenological possibilities: a stable charged slepton, a higgsino-like neutralino, or a sneutrino as the LSP. Different particle spectra result in very different decay patterns, lifetimes and branching ratios which lead to different signals for SUSY searches, as discussed later.

A Fayet–Iliopoulos D -term for the $U(1)_Y$ gauge group is indeed generated in many interesting theoretical scenarios. A kinetic mixing between $U(1)_Y$ and a different $U(1)$ can induce a D -term once the other $U(1)$ develops a D -component vacuum expectation value[5]. The other $U(1)$ can be a part of the gauge group responsible for dynamical SUSY breaking, or an anomalous $U(1)$ in superstring theory whose anomaly is canceled by the Green–Schwarz mechanism. In models with the GMSB it can also be the messenger $U(1)$ [6]. The goal of this letter is, however, to study the effect of the parameter D_Y on phenomenology, and we will, therefore, not discuss its origin any further.

We will only consider constraints from particle physics. In our opinion it is not wise to impose any cosmological constraints on the parameter space for the experimental analysis of collider data. Even though cosmology does provide many useful constraints on parameters of particle physics, cosmology at temperatures between the electroweak scale and nucleosynthesis may be much more complex than usually assumed. For instance, most models of SUSY breaking create cosmological problems, which can be avoided only by invoking inflation at temperatures below the electroweak scale[7]. Such a drastic change removes the constraints that the LSP must be neutral and should not overclose the Universe. Very small R -parity violating couplings

can also evade the cosmological constraints without any consequences to collider phenomenology[8]. The parameter space should be explored without much theoretical prejudice.

We first briefly review the VMSSM parameter space and spectrum. The soft SUSY-breaking parameters at the weak scale are found by solving the renormalization group (RG) equations. In Table 1 we quote the results of numerically running the 1-loop RG equations from the GUT scale down to 500 GeV as a function of m_0^2 , $M_{1/2}$, and A_0 , for $\tan\beta = 10$ as an example. The parameters μ and B run “by themselves”, and one can, therefore, specify their input values at the weak scale.

It is necessary to check that the electroweak symmetry has been broken and that $M_Z = 91$ GeV. This is done by choosing μ^2 such that

$$\mu^2 = -\frac{M_Z^2}{2} + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}, \quad (2)$$

where $\tan\beta$ is the ratio of Higgs boson vacuum expectation values, v_u/v_d . Another condition which must be satisfied involves the B -term. Once $\tan\beta$ is specified, the B -parameter is uniquely determined and is related to the pseudoscalar Higgs mass squared,

$$m_A^2 = m_{H_d}^2 + m_{H_u}^2 + 2\mu^2 = 2\frac{B\mu}{\sin(2\beta)}. \quad (3)$$

To prevent a runaway behavior in the Higgs scalar potential m_A^2 must be positive. After imposing Eqs. (2,3), the VMSSM contains only four extra real free parameters: m_0^2 , $M_{1/2}$, A_0 , $\tan\beta$, plus a discrete choice, $\text{sign}(\mu)$.

Table 1 indicates the structure of the particle spectrum: colored sparticles are heavier than sparticles that only transform under $SU(2)_L \times U(1)_Y$ which in turn are heavier than those that only transform under $U(1)_Y$. Furthermore we can numerically evaluate μ^2 with the help of Eq. (2),

$$\begin{aligned} \mu^2 = & 2.18(M_{1/2})^2 + 0.09m_0^2 + 0.10(A_0)^2 + \\ & + 0.39M_{1/2}A_0 - \frac{1}{2}M_Z^2, \end{aligned} \quad (4)$$

for $\tan\beta = 10$. From gluino searches we find $M_{1/2} \gtrsim 77$ GeV (for $M_3 \gtrsim 200$ GeV), and therefore $\mu^2 \gtrsim 2.14M_2^2$. We can then safely say that the lightest neutralino is an almost pure B-ino of mass $m_{\chi_1^0} \simeq M_1$ [9].

Table 1: SUSY-breaking parameters at a scale of 500 GeV from the 1-loop RG equations with the VMSSM boundary conditions at $M_{GUT} = 1.86 \times 10^{16}$ GeV, for (A) the first/second generation sfermions and (B) the rest with $\tan \beta = 10$. The masses of first/second generation fermions have been neglected, and $h_t(m_t) = 165/(174 \sin \beta)$ was used. The table is to be read as follows: each soft parameter is a linear combination of the input parameters, with the coefficients given in the table. For example, $m_{H_d}^2 = 0.95m_0^2 + 0.38(M_{1/2})^2 - 0.01(A_0)^2 - 0.04M_{1/2}A_0 - 1/2D_Y$ and $A_{\tilde{d}} = A_0 + 3.41M_{1/2}$.

(A)	m_0^2	$(M_{1/2})^2$	D_Y		A_0	$M_{1/2}$
$m_{\tilde{Q}}^2$	1	5.62	1/6	$A_{\tilde{u}}$	1	3.44
$m_{\tilde{L}}^2$	1	0.50	-1/2	$A_{\tilde{d}}$	1	3.41
$m_{\tilde{U}}^2$	1	5.21	-2/3	$A_{\tilde{e}}$	1	0.67
$m_{\tilde{D}}^2$	1	5.17	1/3	-	-	-
$m_{\tilde{E}}^2$	1	0.15	1	-	-	-

(B)	m_0^2	$(M_{1/2})^2$	$(A_0)^2$	$M_{1/2}A_0$	D_Y		A_0	$M_{1/2}$
$m_{\tilde{Q}_3}^2$	0.63	4.70	-0.04	-0.14	1/6	$A_{\tilde{t}}$	0.28	2.04
$m_{\tilde{L}_3}^2$	0.99	0.50	-0.00	-0.00	-1/2	$A_{\tilde{b}}$	0.85	3.12
$m_{\tilde{t}}^2$	0.28	3.45	-0.07	-0.26	-2/3	$A_{\tilde{\tau}}$	0.98	0.64
$m_{\tilde{b}}^2$	0.97	5.09	-0.01	-0.03	1/3	M_1	0	0.43
$m_{\tilde{\tau}}^2$	0.98	0.14	-0.01	-0.00	1	M_2	0	0.83
$m_{H_d}^2$	0.95	0.38	-0.01	-0.04	-1/2	M_3	0	2.61
$m_{H_u}^2$	-0.08	-2.15	-0.10	-0.39	1/2	-	-	-

There are two LSP candidates: the right-handed scalar tau ($\tilde{\tau}_R$) and the lightest neutralino (χ_1^0). It is easy to see that χ_1^0 is always the LSP unless $m_0^2 \lesssim (0.04M_{1/2}^2 - 1890) \text{ (GeV)}^2$, for $\tan\beta = 10$. In theories with the GMSB one can actually have a $\tilde{\tau}_R$ LSP for a larger portion of the parameter space if the number of messengers (N) is large enough[3].

In the LMSSM the Fayet–Iliopoulos D -term (D_Y) changes the mass squared parameters of all the scalars to $m_{\tilde{F}}^2 = m_{\tilde{F},V}^2 + Y_{\tilde{F}}D_Y$ at some energy scale, where the subscript V stands for VMSSM and $Y_{\tilde{F}}$ is the hypercharge of the scalar $\tilde{F}$. Note that $Y_{\tilde{F}}D_Y$ is flavor-blind and, therefore, the flavor-changing constraints are safely avoided.

There is one very important simplification which is peculiar to the parameter D_Y . D_Y runs by itself and hence it does not matter at what energy scale the scalar masses-squared are modified. Therefore, it is convenient to calculate $m_{\tilde{F},V}^2$ at the weak scale from the inputs m_0^2 , $M_{1/2}$, and A_0 (see Table 1) and add the weak-scale value of $Y_{\tilde{F}}D_Y$.

Similar to the VMSSM, electroweak symmetry breaking imposes constraints on the parameter space. One way to satisfy Eq. (2) is to choose D_Y such that

$$\frac{M_Z^2}{2} + \mu^2 - \frac{m_{H_d,V}^2 - m_{H_u,V}^2 \tan^2 \beta}{\tan^2 \beta - 1} = \frac{D_Y}{2 \cos 2\beta}. \quad (5)$$

Note that the form of Eq. (3) is unchanged. The free parameters are, therefore,

$$m_0^2, M_{1/2}, A_0, \tan\beta, \text{ and } \mu. \quad (6)$$

Unlike in the VMSSM, μ is a free parameter in the LMSSM. It does not, for example, have to be larger than M_2 or even M_1 . This will change phenomenology drastically. Note that exactly the same strategy can be followed to add D_Y as an extra parameter to models with the GMSB.

Varying D_Y (or μ) affects different parameters in different ways. For negative D_Y , $\tilde{E}$, $\tilde{D}$, and $\tilde{Q}$ become lighter (the effect on $m_{\tilde{D}}^2$ and $m_{\tilde{Q}}^2$ is, however, small because of their hypercharges), while other sfermions become heavier. In this case the absolute value of the μ -term is larger than in the VMSSM (see Eq. (5)). If D_Y is large enough compared to $M_{1/2}$, $\tilde{\tau}_R$ becomes the LSP. Note that, unlike in the VMSSM, this happens for a large range of values of m_0^2 . Fig. 1 depicts the nature of the LSP in the $(\mu, M_{1/2})$ plane for fixed values of m_0^2 and $\tan\beta$. For smaller (larger) values of m_0^2 or larger (smaller) values of $\tan\beta$, the size of the physically allowed region decreases

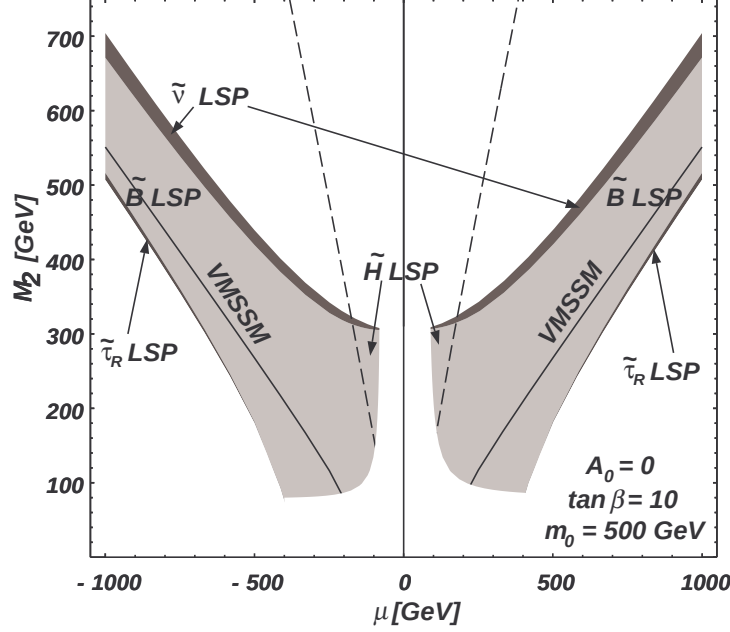


Figure 1: Parameter space analysis indicating the nature of the LSP. The solid line indicates the points allowed by the VMSSM and the dashed line represents points where the gaugino content of χ_1^0 is 50%. $A_0 = 0$, $m_0^2 = 500^2$ (GeV) 2 and $\tan \beta = 10$. The bounds $m_A > 65$ GeV, $m_{\tilde{\nu}} > 43$ GeV, $m_{\tilde{\tau}} > 67$ GeV (if $m_{\tilde{\tau}} < m_{\chi_1^0}$), and $m_{\chi_1^\pm} > 65$ GeV were imposed.

(increases), but the qualitative features of the figure remain the same (with the exception of large $\tan \beta \gtrsim 30$, see below).

For positive D_Y , $\tilde{L}$ and $\tilde{U}$ become lighter, while all other sfermion masses increase. In this case the absolute value of μ is smaller than in the VMSSM. The consequences of this are many (see Fig. 1). $\tilde{\nu}_\tau$ can become the LSP. If μ is small enough, χ_1^0 can be the LSP but with a large higgsino content. The mass splitting between $\tilde{t}$'s is enhanced with respect to the VMSSM. Finally, if $\tan \beta \gtrsim 30$ and μ is large, the left-handed $\tilde{\tau}$ can become the LSP due to left-right mixing in the mass squared matrix.

We would like to draw attention to the *existence* of different particle spectra for different regions in the parameter space rather than the size of those regions (see Fig. 1). Like the VMSSM, the LMSSM should be considered as a parameterization and not a model, and the fact that diverse spectra can

occur is what interests us.

Next we discuss interesting aspects of the phenomenology of the spectra outlined above semi-quantitatively.

If $\tilde{\tau}$ is the LSP, heavy stable charged particles become a good signature for SUSY searches. An analysis of this situation was done in the context of models with the GMSB where the $\tilde{\tau}_R$ is the LSP[10]. Heavy stable charged particles might be found by looking for an excess of hits in the muon chambers, or tracks with anomalously large dE/dx in the tracking chambers.

If the LSP is a higgsino-like neutralino, the phenomenology is very different from the VMSSM case, where the LSP is an almost pure B-ino. In this case there are four fermions relatively close in mass: χ_1^0 , χ_2^0 and $\chi_1^\pm$, which are all higgsino-like. In this situation experimental searches are much harder. Chargino searches become more difficult because the mass splitting between $\chi_1^\pm$ and χ_1^0 becomes very small ($m_{\chi_1^\pm} - m_{\chi_1^0} \simeq m_W^2/M_{1/2}$ in the limit of $M_2 \gg \mu, m_W$), and $\chi_1^\pm$ will decay into missing transverse energy ($\cancel{E}_T$) plus low energy leptons or jets ($E_{l,j} \simeq 6$ GeV if $M_{1/2} = 600$ GeV). Experimental searches for chargino signals at the Tevatron usually require that $E_T^{l,j} > 15$ GeV[2, 11].

At hadron machines the amount of $\cancel{E}_T$ is reduced because of the small coupling between first and second generation squarks and $\chi_1^{0,\pm}$. The main decay mode of a squark is $\tilde{q} \rightarrow q\chi_{3,4}^0$ or $q'\chi_2^\pm$, and the heavier chargino/neutralinos, which are gaugino-like, further decay via, *e.g.*, $\chi_2^\pm \rightarrow \chi_1^0 H^\pm$. The decay chains are therefore much longer and the amount of $\cancel{E}_T$ should decrease. It is interesting to note that there might be a significant increase in the number of top quark, b-jet, and τ events because of the production of heavy Higgs boson states ($H^{0,\pm}$, A^0), which have large branching ratios into third generation fermions.

The clean tri-lepton signature at hadron machines will decrease by an order of magnitude mainly because of the smaller leptonic branching ratio for χ_2^0 and $\chi_1^\pm$. Note that this effect is not restricted to the pure higgsino-like neutralino limit, but also applies to a mixed χ_1^0 [2].

If the LSP is $\tilde{\nu}_\tau$, the decay modes of the heavier particles change dramatically. There are different possibilities, depending on $m_{\tilde{l}}$ and $m_{\chi_1^0}$.

If $m_{\tilde{l}} < m_{\chi_1^0}$ the main decay mode for sleptons is $\tilde{l} \rightarrow \tilde{\nu} jj$ or $\tilde{l} \rightarrow \tilde{\nu} l' \nu_{l'}$. Charginos, on the other hand, decay into two particles, namely $\chi^\pm \rightarrow \tilde{\nu} l$ or $\rightarrow \tilde{l} \nu$. The pair production of two sleptons at an e^+e^- machine will yield,

for instance, $lj\cancel{E}$, which is the typical chargino pair production signal in the VMSSM. The production of a chargino-pair will yield acoplanar leptons plus $\cancel{E}$, which is the typical slepton signal at e^+e^- machines in the VMSSM. The two leptons, however, do not have to be of the same flavor. There are, of course, ways of distinguishing a slepton signature in the VMSSM from the chargino signal in this scenario because the cross sections and angular distributions are quite different.

Another important feature is the visible decay $\chi_1^0 \rightarrow \tilde{l}l$. This makes the production $q\bar{q} \rightarrow \chi_1^0\chi_1^0$ a feasible SUSY signature. Furthermore squarks decay dominantly as $\tilde{q} \rightarrow q\chi_1^0$ because $\tilde{U}$ is much lighter than $\tilde{Q}$ or $\tilde{D}$, and hence the squarks produced are dominantly $\tilde{U}$. This can lead to a rather impressive four leptons plus jets plus $\cancel{E}_T$ signature at hadron machines. The total fraction of $4l$ events is only about 0.5% because typically $BR(\chi_1^0 \rightarrow \tilde{l}l) \simeq 1/3$ and $BR(\tilde{l} \rightarrow \tilde{\nu}_l\bar{l}'\nu_{l'}) \simeq 20\%$ for $l, l' = e$ or μ , but they have much lower backgrounds [2].

In the case $m_{\tilde{l}} > m_{\chi_1^0}$ both the $\chi_1^\pm$ and the $\tilde{l}$ decay into two on-shell particles ($\tilde{l} \rightarrow \chi_1^0 l$). The χ_1^0 , though unstable, is still invisible, because its only allowed decay mode is $\chi_1^0 \rightarrow \nu\tilde{\nu}$. This scenario has, therefore, four “virtual LSPs” (3 $\tilde{\nu}$ and the χ_1^0). In this case the amount of $\cancel{E}_T$ in hadron machines is virtually unchanged with respect to the VMSSM[12]. Note that the clean tri-lepton signature is enhanced (given that $\chi_2^0 \rightarrow \tilde{l}l$ is allowed with reasonable branching ratio) because both the $\chi_1^\pm$ and the $\tilde{l}$ always decay into one charged lepton.

Finally, there is another type of signature, which has no VMSSM analog, if the sneutrino is the LSP and $\tan\beta \gtrsim 4$: visible sneutrino decays, $\tilde{\nu}_l \rightarrow l^-\tau^+\tilde{\nu}_\tau$. In this case the first and second generation sneutrinos are heavier than $\tilde{\nu}_\tau$ enough to decay visibly. The other allowed sneutrino decays are $\tilde{\nu}_l \rightarrow \nu_l\tilde{\nu}_\tau\bar{\nu}_\tau$ and $\tilde{\nu}_l \rightarrow \nu_l\tilde{\nu}_\tau^*\nu_\tau$. For $\tan\beta = 10$, $m_0^2 = 500^2(\text{GeV})^2$, $m_{\tilde{\nu}_\tau} = 75$ GeV and $M_1 = 185$ GeV, $\Delta m \simeq 15$ GeV, and the visible branching ratio is approximately 7%. In this scenario, there is a very striking signature for $\tilde{\nu}_l\tilde{\nu}_l^*$ ($l = \mu, e$) production in e^+e^- machines if one of the sneutrinos decays visibly and the other invisibly. One expects to see $l^\pm\tau^\mp$ plus $\cancel{E}_T$ for $2 \times (.07 \times .93) = 13\%$ of all $\tilde{\nu}_l\tilde{\nu}_l^*$ produced, for the parameters mentioned earlier. The main backgrounds for this signal are $e^+e^- \rightarrow W^+W^-$ and $\gamma\gamma \rightarrow \tau^+\tau^-$. However, simple kinematic cuts should efficiently suppress these events, because their kinematics are quite different from the signal's.

A systematic study of the appropriate cuts is beyond the scope of this letter. There is also the possibility that $\tilde{\nu}_l$ decays with a displaced vertex, if Δm is small enough. In this case, however, the visible branching ratio is significantly smaller because of the phase space reduction due to the tau mass.

In summary, we have shown that the so-called “Minimal Supergravity Inspired” Supersymmetric Standard Model is too restrictive as far as collider phenomenology is concerned. We proposed the addition of only one extra parameter to the VMSSM, the Fayet–Iliopoulos D -term for $U(1)_Y$, and showed that it is capable of yielding a much more diverse phenomenology while still satisfying all experimental constraints.

While the VMSSM almost always yields a B-ino-like LSP, our LMSSM also allows $\tilde{\nu}$, $\tilde{\tau}$ or Higgsino-like χ_1^0 LSP. We have verified that for each one of these cases there are important phenomenological consequences, including new signatures for SUSY and the disappearance of other “standard” signatures. Even though we do not advocate the LMSSM as *the* model of SUSY breaking, we emphasize that is a much less restrictive, and yet workable, parameterization of the SUSY breaking sector.

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